Supernova relic neutrinos and cosmic chemical evolution

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Refs.: Ashida, Nakazato & Tsujimoto, ApJ. **953** (2023) 151
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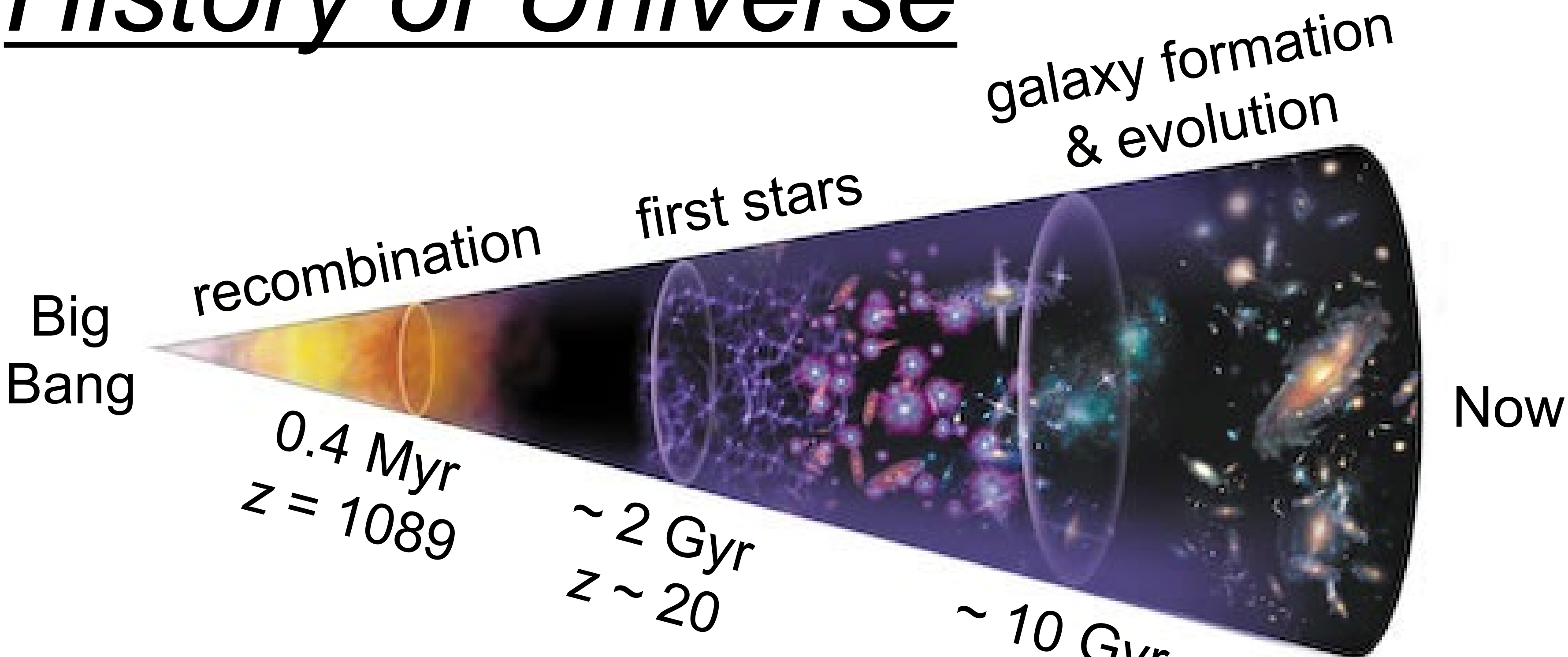
History of Universe

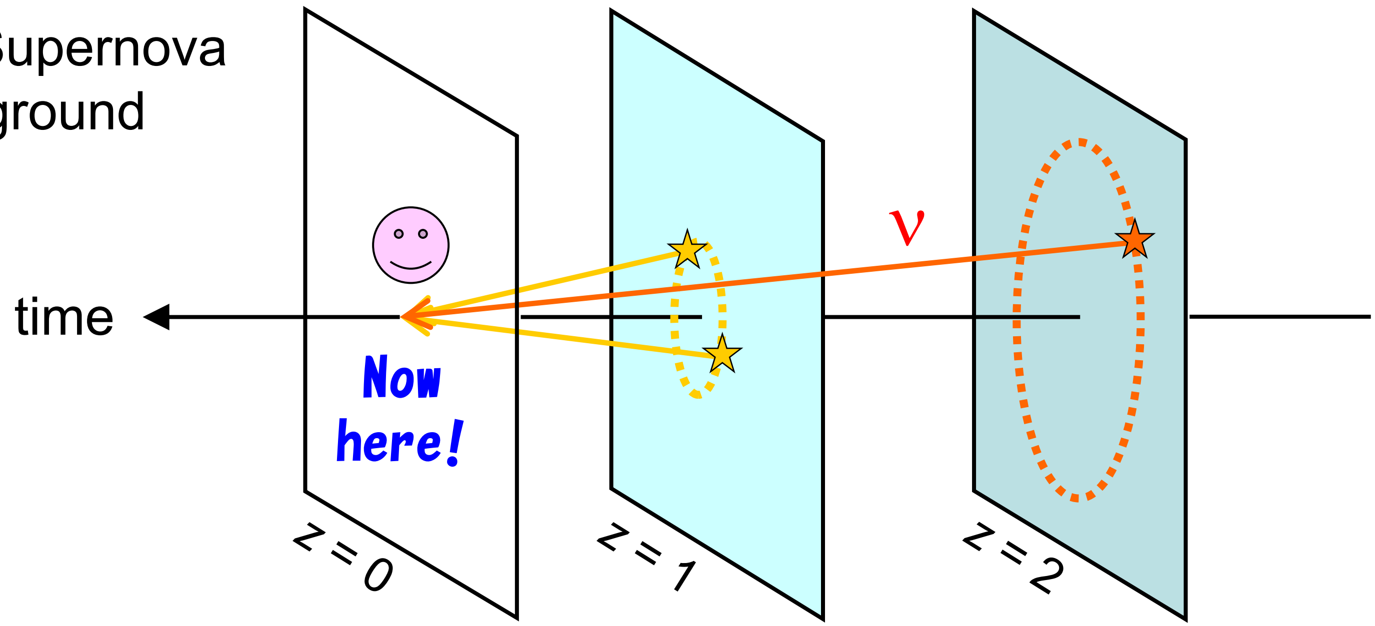


- The Universe is expanding!
- Cosmological redshift *z* denotes ``time''.

Many generations of stars have exploded!

Supernova relic neutrinos

a.k.a. Diffuse Supernova Neutrino Background (DSNB)



- Neutrinos emitted by all core-collapse SNe in the causally-reachable universe constitute diffuse background radiation.
- Can we detect the SN relic neutrinos? What determines their flux and spectrum?

What determines BG luminosity?

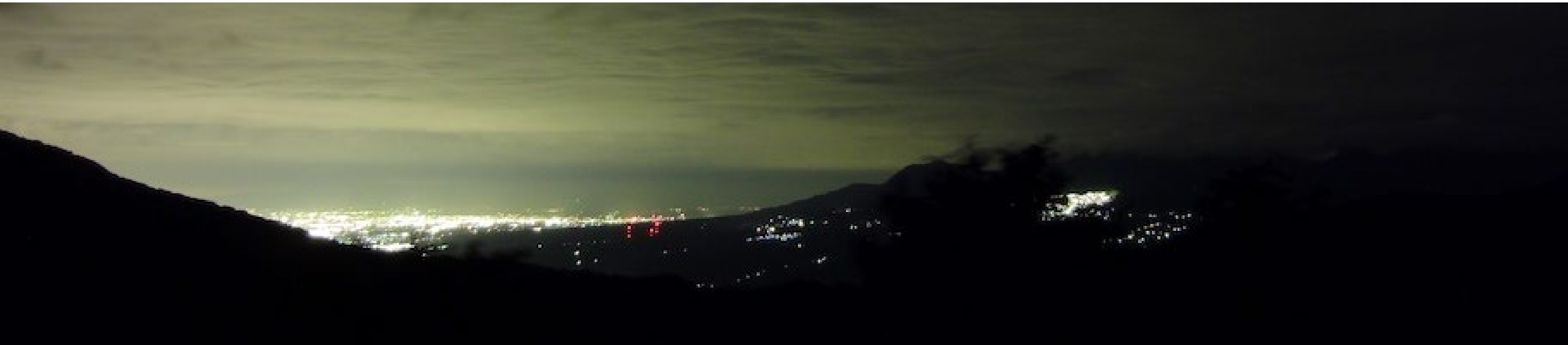
⇓

supernova relic neutrinos

- luminosity of a source → NS or BH
- the source number
- distance to sources
  - cosmological redshift in the expanding universe

} star formation history

- also, neutrino oscillation parameters



Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z\right)$$

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{CC}}(z) \left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle \frac{dz}{H_0\sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda}}$$

- Spectrum of supernova neutrinos: $\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle$
- Cosmological parameters:

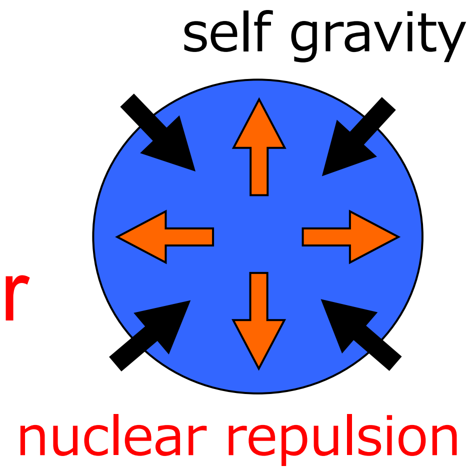
  $H_0 = 67.7$ km/s/Mpc, $\Omega_{\mathrm{m}} = 0.31$, $\Omega_\Lambda = 0.69$

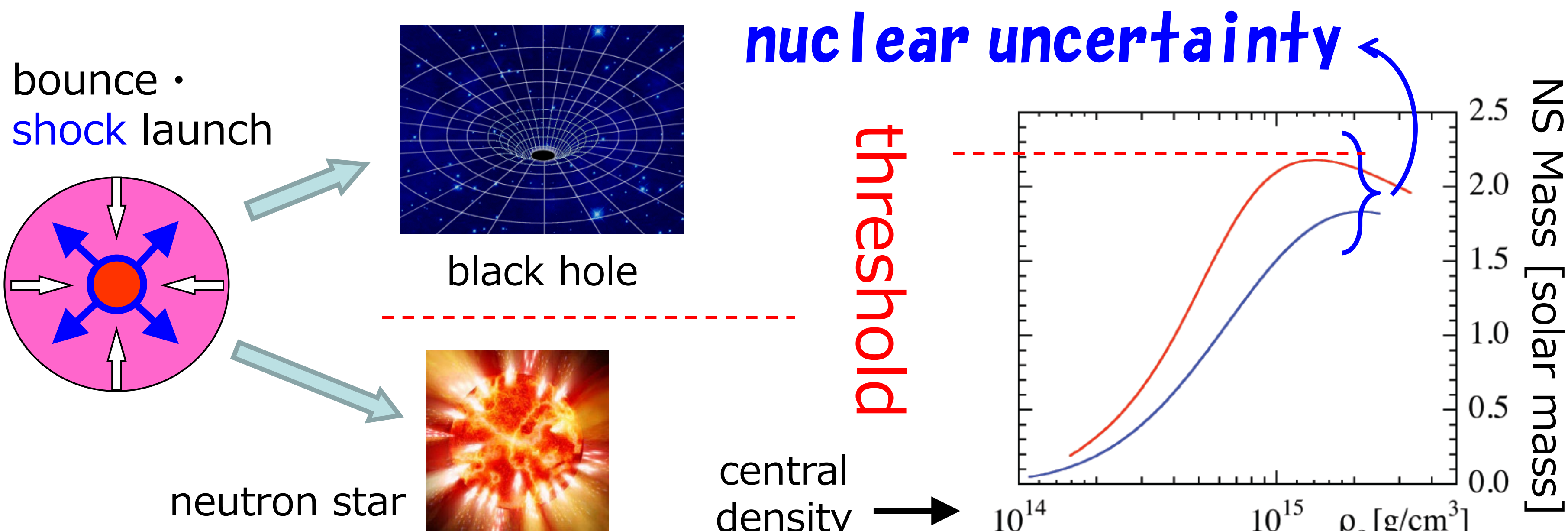
- Core-collapse rate: $R_{\mathrm{CC}}(z)$

（from Tsujimoto, 2023）

Neutron stars vs. Black holes

- Neutron stars sustain the self gravity by the nuclear repulsion.
- NS mass sustained by the nuclear repulsion has the upper limit.
- BH is formed beyond the upper limit.

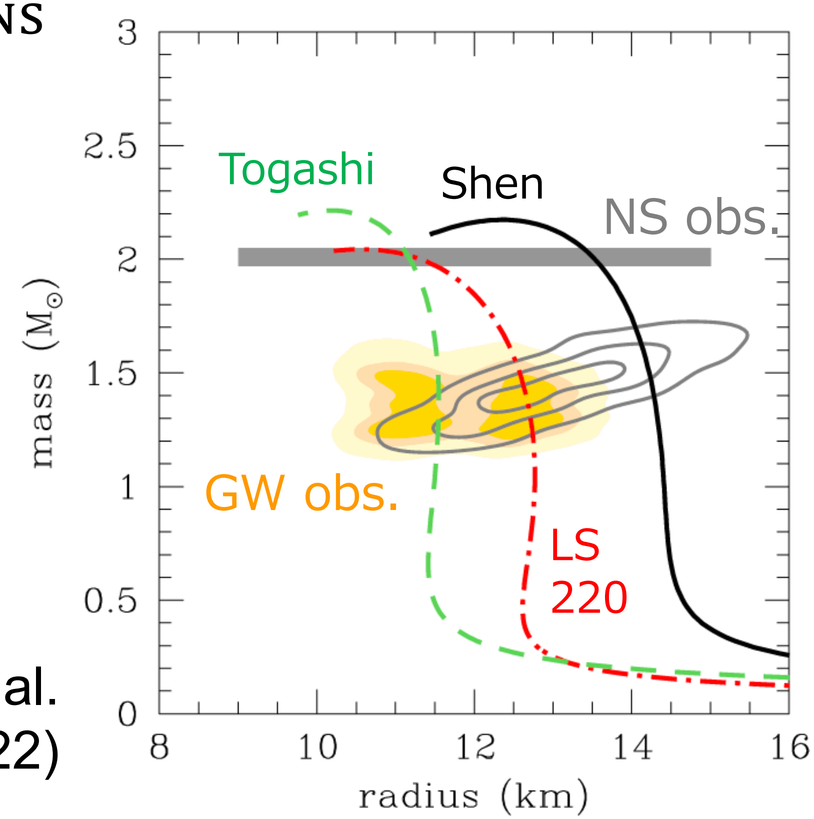




Nuclear equation of state

- Impacts on the neutrino emission:
  - for NS case, smaller radius → larger emission

    ∵ total energy is $E \sim \frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}}$
  - for BH case,
    higher maximum mass
    → larger emission
- We adopt 3 types of EOS in this study.



Nakazato et al.
Astrophys. J. **925**, 98 (2022)

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have top-heavy IMF
  2. Progenitors with ≥ $18M_\odot$ becomes BH

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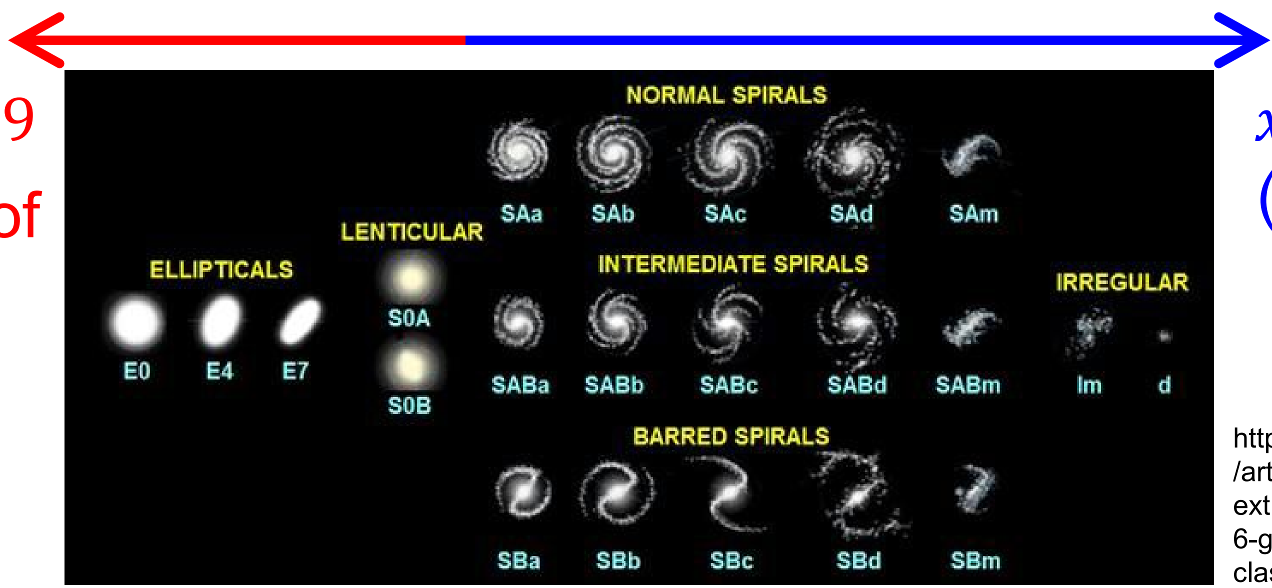
- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have top-heavy IMF
  2. Progenitors with $\geq 18 M_{\odot}$ becomes BH
- Initial mass function（IMF）: $\psi_{\rm IMF} = \frac{dN}{dM} \propto M^{x-1}$

$x = -0.9$

fraction of massive stars is higher



$x = -1.35$
(Salpeter)

https://www.cloudynights.com/articles/cat/articles/basic-extragalactic-astronomy-part-6-galaxies-discovery-and-classification-r3248

According to Tsujimoto (2023)

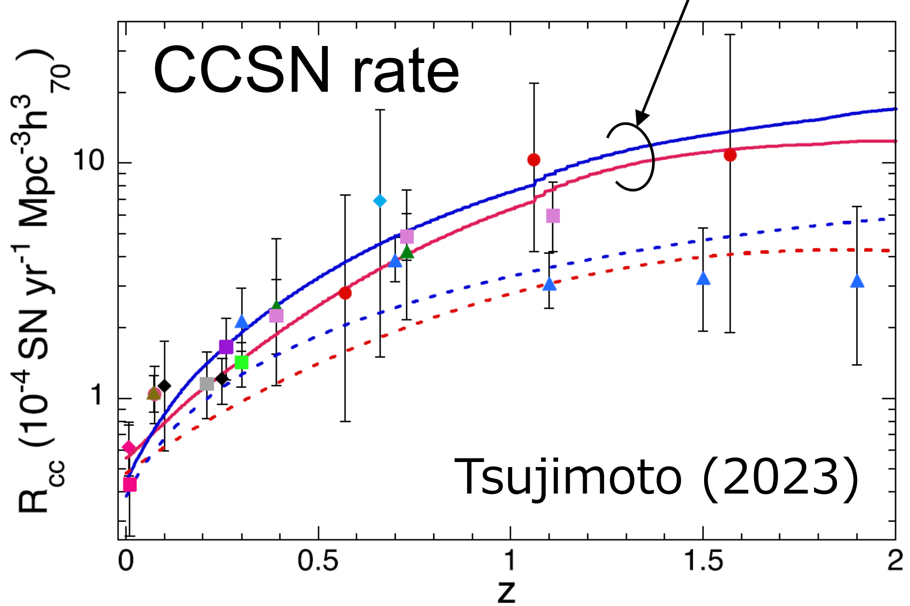
- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have top-heavy IMF
  2. Progenitors with ≥ $18M_\odot$ becomes BH

- CCSN rate: $\dot{\rho}_*(z) \frac{\int_{8M_\odot}^{18M_\odot} \psi_{\mathrm{IMF}}(M)dM}{\int_{0.1M_\odot}^{100M_\odot} M\cdot\psi_{\mathrm{IMF}}(M)dM}$

  - ➢ cosmic star formation rate, $\dot{\rho}_*(z)$, is from

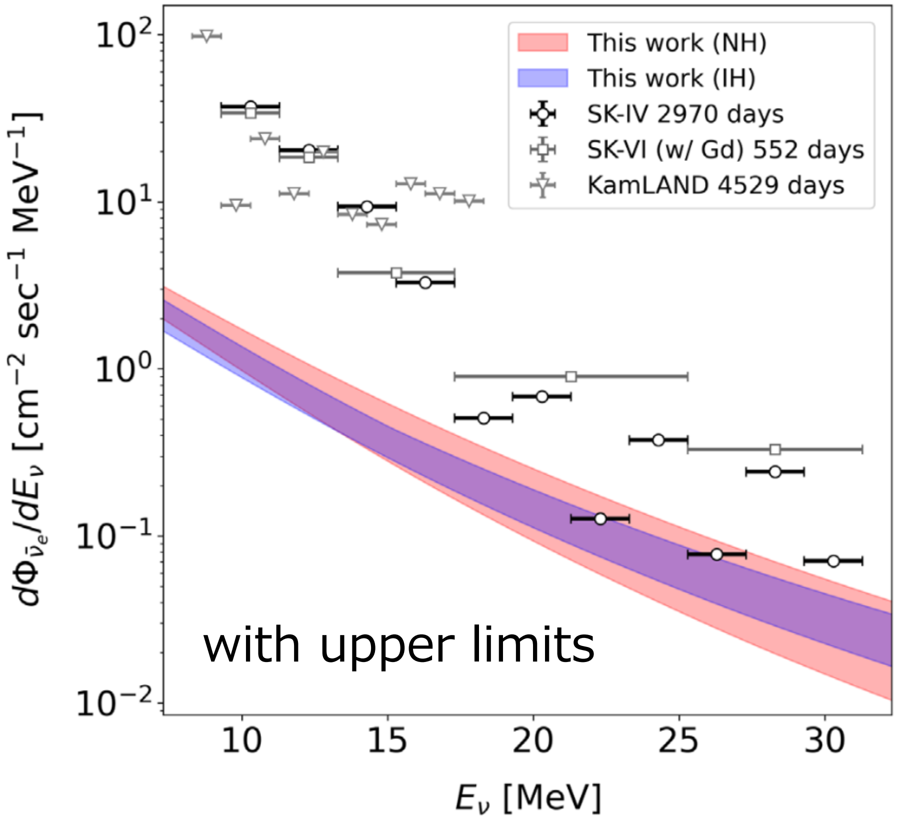
Hopkins & Beacom (2006)

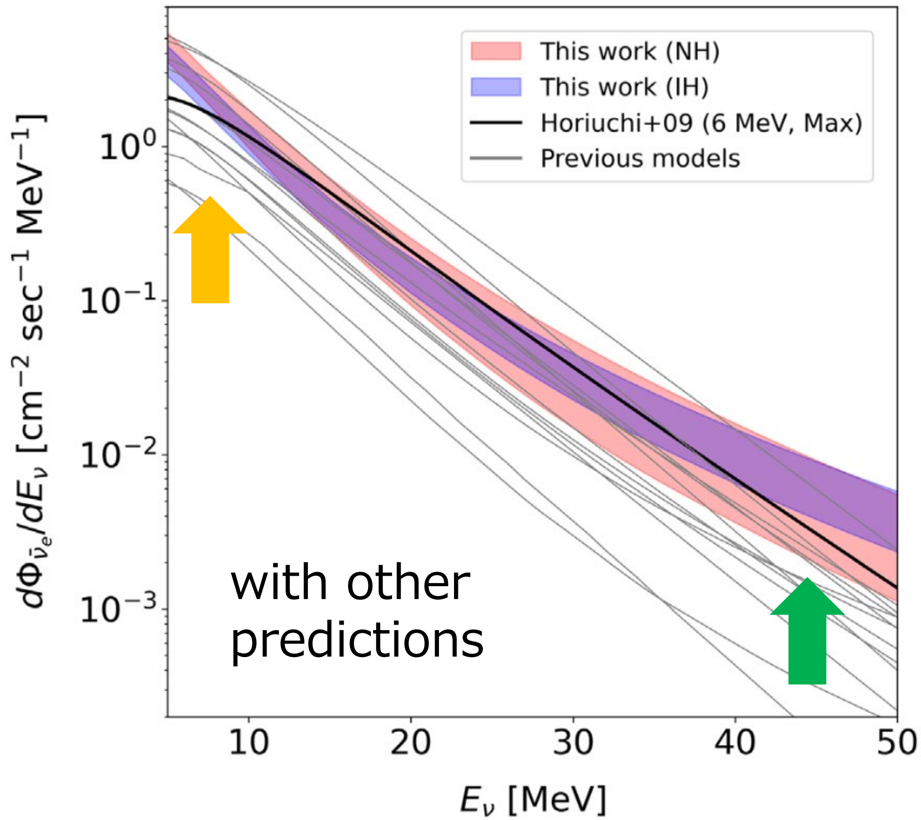
Madau & Dickinson (2014)



SRN flux

Ashida, Nakazato & Tsujimoto (2023)





- Comparing with other work, enhancement at low ($\lesssim$10 MeV) and high ($\gtrsim$30 MeV) energies

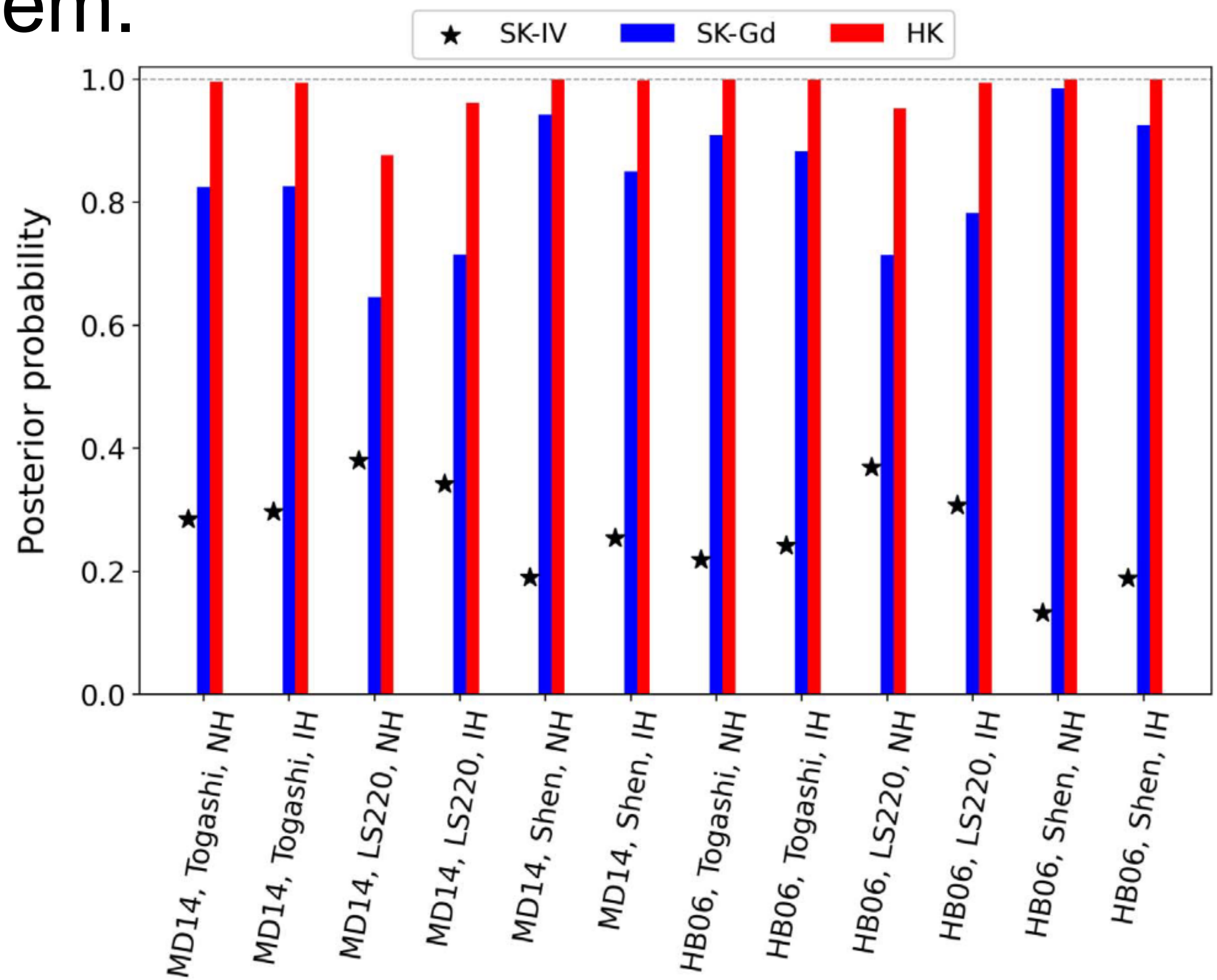
→ due to high *z* and BH sources, respectively

Signal significance

- SRN + BG is tested against BG only using Bayes' theorem.

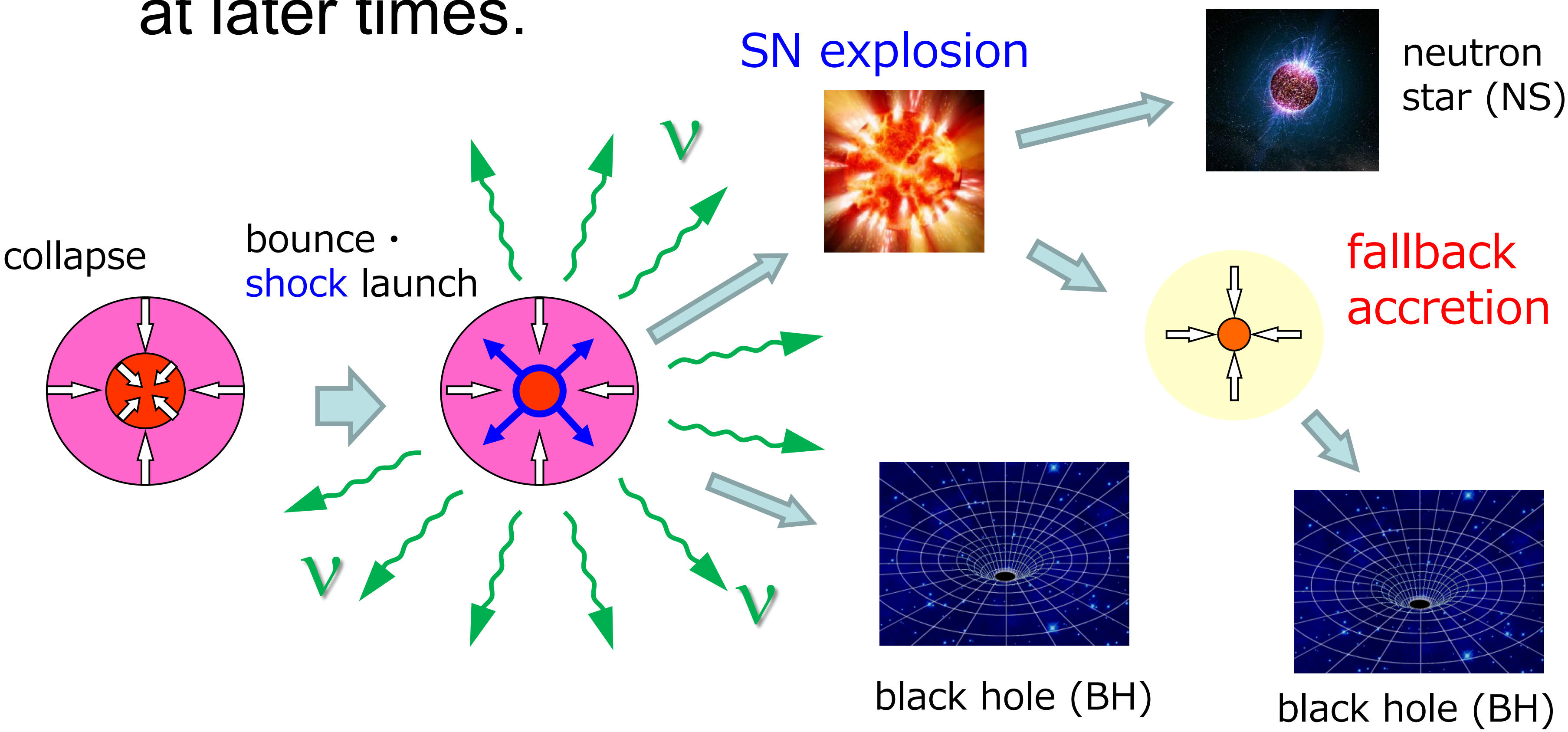
SK-Gd (10 yr): 70% neutron-tag efficiency

HK (10 yr): neutron-tag efficiency same with SK-IV



Another candidate

- Fallback accretion induced BH formation
  - ➢ Successful SN explosions accompanied by a substantial fallback that leads to a BH formation at later times.



Why we study them?

- If exist, their impact is large.

→ The binding energy $E_{\rm bin}$ of maximum mass NS is fully converted to neutrinos.

  - $E_{\rm bin}$ = (baryon mass − gravitational mass) c^2

- For example (in Togashi EOS):

  - canonical mass ($1.32M_\odot$) NS

    $E_{\rm bin} = (1.47 - 1.32)M_\odot c^2 = 2.7\times10^{53}$ erg

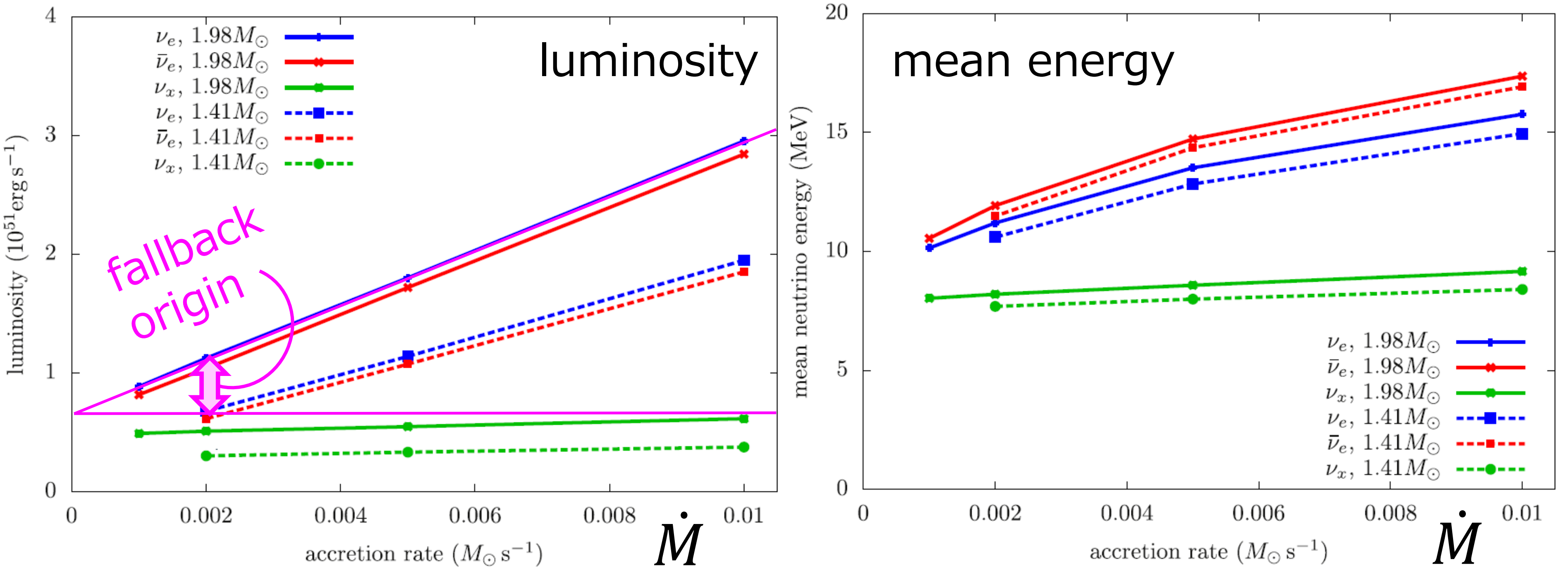
  - maximum mass ($2.21M_\odot$) NS

    $E_{\rm bin} = (2.70 - 2.21)M_\odot c^2 = 8.8\times10^{53}$ erg

Neutrinos from FB accretion

- Akaho, Nagakura & Foglizzo (2024)
  - ➢ Steady-state neutrino emission from fallback mass accretion onto PNS (1.41 and 1.98$M_\odot$)
    → $M_g = 1.98M_\odot$ corresponds to $M_b = 2.35M_\odot$
- Combining following 3 components:
  1. Core-collapse of massive star
  2. Cooling of 1.98$M_\odot$ proto-NS cooling
  3. Fallback accretion of 0.35$M_\odot$
     - ➢ Max. mass of NS is $M_b = 2.70M_\odot$ (Togashi).
     - ➢ We evaluate ν spectra emitted from fallback.

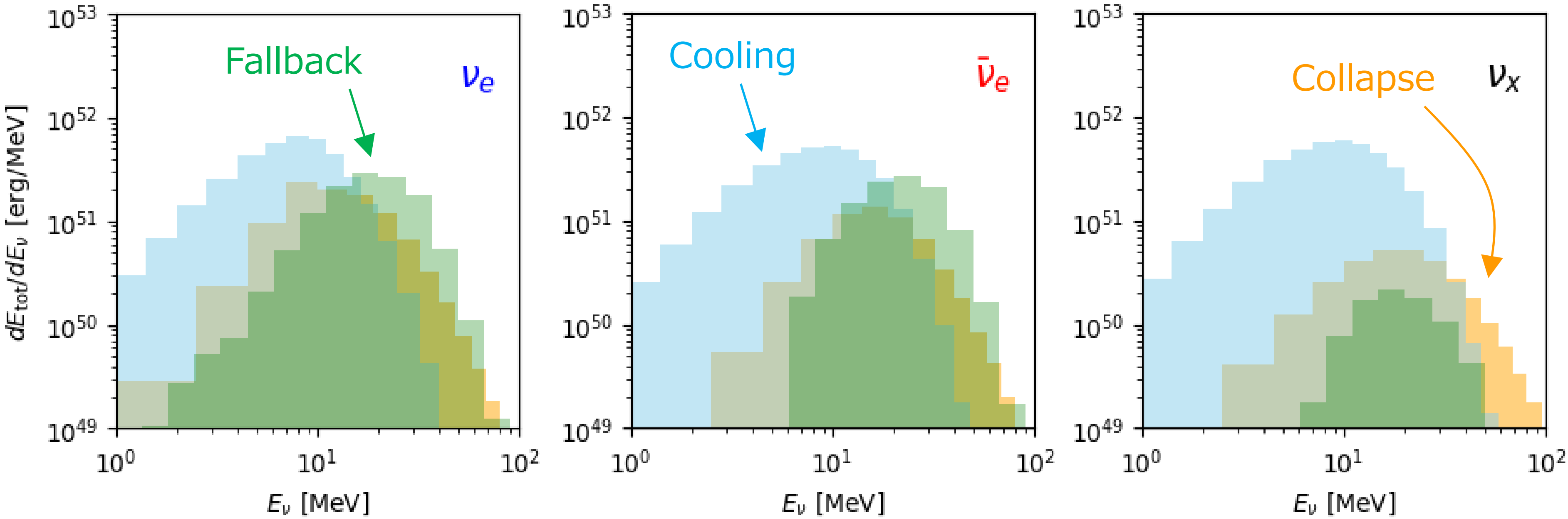
According to Akaho+ (2024)



- Fallback produces high-energy ν_e and $\bar{\nu}_e$.
  - ➢ Their luminosity gets higher for larger $\dot{M}$.
- Emission of ν_x is from inside PNS (2 MeV).
  - ➢ Offsets of ν_e and $\bar{\nu}_e$ luminosities are as well.

Model description

- Neutrino spectra of individual component.



  - ➢ Resultant total emission energy: 8.7×10^{53} erg

- In this study, we assume that f_{FB} to be the fraction of SNe associating FB induced BH formation among all CCSNe.

SRN flux

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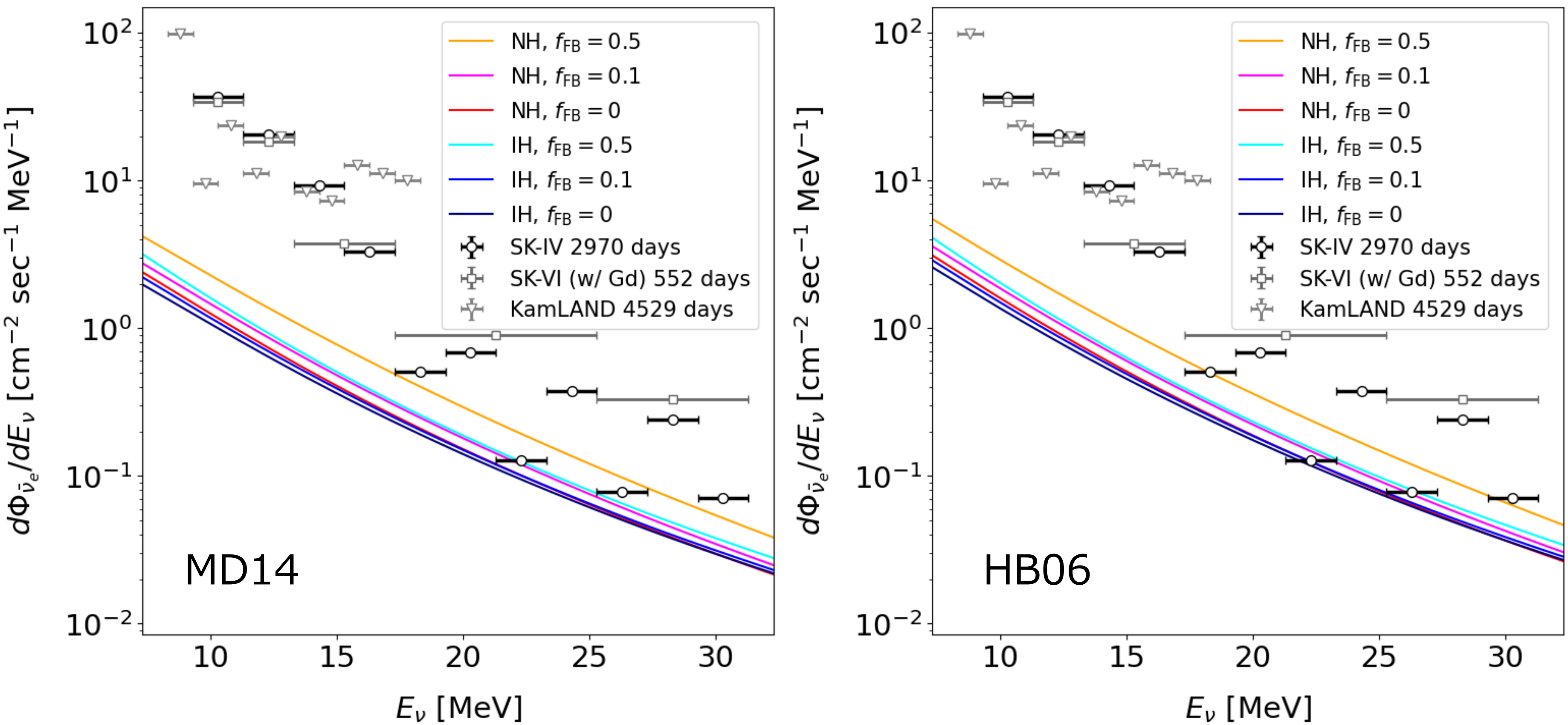
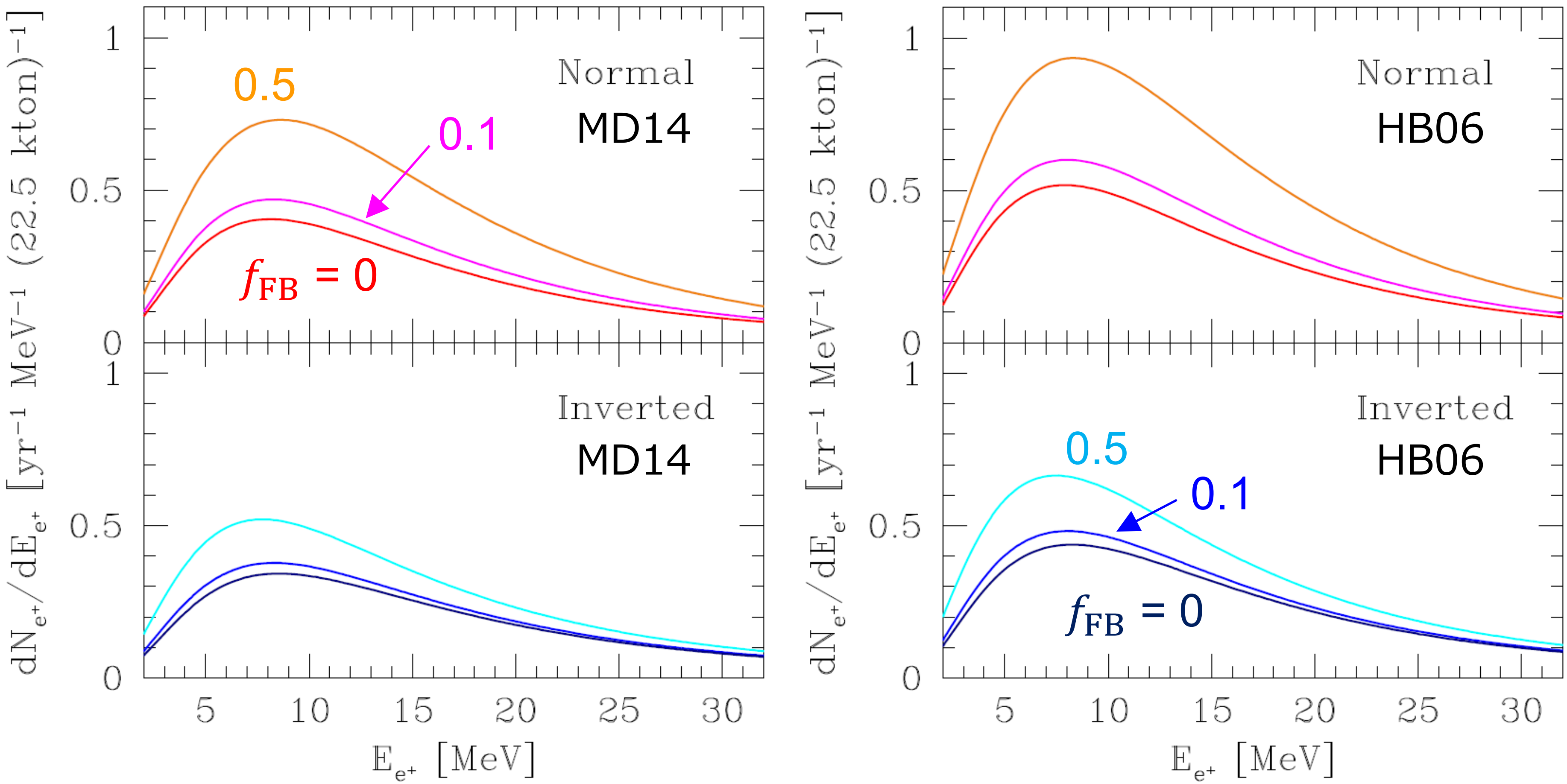


- The impact is larger for NH case
  - ∵ The fallback accretion produce mainly ν_e and $\bar{\nu}_e$.
- NH, HB06, f_{FB} = 0.5 case is close to limits.

Event rate

Nakazato et al. in prep.



- For NH and f_{FB} = 0.5 case, event rate in the detectable range (16—30 MeV) gets twice.

Summary

- Supernova relic neutrino (DSNB) flux is evaluated based on the recent Galactic chemical evolution model.
  - Both the core-collapse rate and fraction of BH formations are higher than in previous models.
  - The detection will be achieved in near future.
- Contribution of the fallback induced BH formations enhances the event rate.
  - They produce high-energy ν_e and $\bar{\nu}_e$.
  - Their fraction may be constrained by SRN.